

Charm production in antiproton-nucleus collisions at the J/ψ and the ψ' thresholds

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Abstract

We discuss the production of charmonium states in antiproton-nucleus collisions at the ψ' threshold. It is explained that measurements in $\bar{p}A$ collisions will allow to get new information about the strengths of the inelastic $J/\psi N$ and $\psi' N$ interaction, on the production of Λ_c and \bar{D} in charmonium-nucleon interactions and for the first time about the nondiagonal transitions $\psi' N \rightarrow J/\psi N$. The inelastic J/ψ -nucleon cross section is extracted from the comparison of hadron-nucleus collisions with hadron-nucleon collisions. We extract the total J/ψ -nucleon cross section from photon-nucleon collisions by accounting for the color transparency phenomenon within the frame of the GVDM (Generalized Vector meson Dominance Model). We evaluate within the GVDM the inelastic ψ' -nucleon cross section as well as the cross section for the nondiagonal transitions. Predictions for the ratio of J/ψ to ψ' yields in antiproton-nucleus scatterings close to the threshold of ψ' production for different nuclear targets are presented.

1 Introduction

During the last two decades significant attention was given to the absorption of charmonium states produced in heavy ion collisions, see e.g. ref. [1] and references therein. An important role in such evaluation is played by the value of the total and the elastic cross sections for charmonium-nucleon interactions as well as the amplitude for the inelastic transition between J/ψ and ψ' states characterizing the role of color transparency phenomena. The aim of this paper is to extract these cross sections from photoproduction data following ref. [2] and to make predictions for antiproton-nucleus collisions at the ψ' threshold. We demonstrate that in these collisions the cross section for the nondiagonal transition $\psi' + N \rightarrow J/\psi + N$ can be measured. We account for the dependence of the cross sections on energy, and the dependence of the elastic cross section on the momentum transfer.

The charmonium production at the ψ' threshold is well suited to measure the genuine charmonium-nucleon cross sections. At higher energies formation time effects makes the measurement of these cross sections more difficult [3]. These cross sections and the cross section for the nondiagonal transition $\psi' + N \rightarrow J/\psi + N$ are important for the analysis of charmonium production data at SPS-energies [4, 5]. At collider energies, i.e. at RHIC and LHC, the formation time effects will become dominant and charmonium states will be produced only far outside of the nuclei [6]. However, measurements of the genuine charmonium-nucleon cross sections as well as the cross

section for the nondiagonal transition $\psi' + N \rightarrow J/\psi + N$ are also important at collider energies for the evaluation of the interaction of charmonium states with the produced secondary particles.

By using the appropriate incident energy in antiproton-nucleus scattering, the case when the scattering occurs off the nucleons with small internal momenta can be selected. Correspondingly, in this situation off shell effects in the amplitude should be very small and, hence, there will be no significant nuclear corrections due to possible modification of the nucleons in nuclei. In addition, due to the large antiproton-nucleon cross section, those antiprotons which do not undergo absorption at the surface of the nuclear target will lose a significant fraction of their energy. Therefore, at energies close to the threshold the charmonium production is almost impossible inside of the nuclear target.

We discuss in this paper the production of charm at the $p\bar{p} \rightarrow J/\psi, \psi'$ thresholds. To avoid difficulties with the specifics of low energy initial state interaction effects, which are actually included into the partial width of the $J/\psi \rightarrow p\bar{p}$ decay, like those discussed in ref. [7], we will discuss ratios of cross sections, in which the factor $\sigma(p\bar{p} \rightarrow J/\psi, \psi')$ is canceled. We demonstrate that these ratios are well suited to measure the nondiagonal ($\psi' \rightarrow \psi$) cross section as well as the inelastic J/ψ and ψ' cross section. At the same time the momentum of charmonium in the final state is 5 GeV/c in the rest frame of the nuclear target. Hence, one cannot probe in this reaction a possible enhancement of the charmonium-nucleus cross section near threshold of charmonium-nucleus interactions like that described in ref. [8].

The amplitude of the J/ψ photoproduction close to the threshold $E_\gamma \sim 9$ GeV is dominated by the generalized gluon density at large $x_1 - x_2 \sim 0.5$. In such a kinematic, Fermi motion effects may lead to a significant enhancement. However, similar to the quark distribution functions one may expect a suppression reflecting medium modifications of the nucleon structure functions (the analogue of the EMC effect). In a genuine photoproduction experiment it would be very difficult to distinguish the EMC type effect from the absorption due to the final state interaction. However, the combination of a measurement at the GSI of the $\bar{p} + A \rightarrow J/\psi + X$ reaction and of photoproduction at 12 GeV at the Jefferson-lab will make it possible to measure the A -dependence of the nuclear generalized gluon distributions at large x .

The ratio of the elastic to the total $J/\psi N$ cross section has been evaluated long ago in ref. [10] in the Vector meson Dominance Model (VDM), where the energy dependence and the real part of the forward scattering amplitude were neglected and the t dependence of the elastic cross section was effectively adjusted to the data on the soft QCD process of the ρ photoproduction off the nucleon target. We will show in this paper that all these effects and color transparency phenomenon should be taken into account.

In the beginning of this paper we examine the energy dependence of the ratio of the elastic to the total $J/\psi N$ cross section as well as the influence of the real part of the amplitude and treat the t dependence of the elastic cross section within a charmonium model. The final result is that the ratio of the elastic to the total $J/\psi N$ cross section is still small (approximately 5% \div 6.5%) but by a factor ≈ 2.5 larger than that given in the previous evaluation.

In the following section the amplitudes of the GVDM, the elastic form factor and the two-gluon-form factor are described. The amplitudes of the GVDM are described in more detail in the appendix. In the third section the semiclassical Glauber model is described and the predictions for the future GSI experiment are shown. In the fourth section the results of this paper are summarized. The phenomena considered in this paper are complementary to the program of antiproton-nucleus scattering experiments at the GSI range outlined in the recent review [11].

2 Model description and results

In ref. [10] the elastic and the total J/ψ -nucleon cross sections were evaluated within the Vector meson Dominance Model (VDM). In this model, the J/ψ photoproduction amplitude $f_{\gamma\psi}$ and the J/ψ -nucleon elastic scattering amplitude $f_{\psi\psi}$ are related as,

$$f_{\gamma\psi} = \frac{e}{f_\psi} f_{\psi\psi} \quad . \quad (1)$$

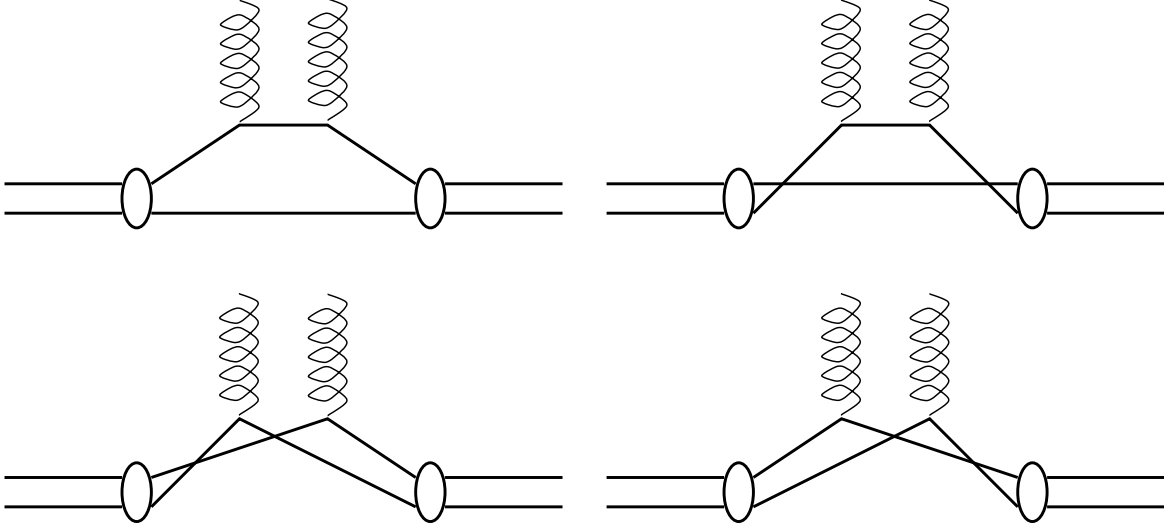


Figure 1: The four leading graphs that contribute to the elastic form factor of the J/ψ

Here, e is the charge of an electron and f_ψ is the $J/\psi - \gamma$ coupling given by,

$$\left(\frac{e^2}{4\pi f_\psi} \right)^2 = \frac{3}{4\pi} \frac{\Gamma(V \rightarrow e\bar{e})}{m_\psi} . \quad (2)$$

A similar relation like eq. (1) can be written also for the ψ' . From the optical theorem,

$$\sigma_{tot}(J/\psi N) = \frac{I_{\psi\psi}(t=0)}{2p_{cm}E_{cm}} , \quad (3)$$

where $I_{\psi\psi}$ is the imaginary part of $f_{\psi\psi}$ and the differential elastic cross section,

$$d\sigma_{el}/dt = \frac{1}{64\pi p_{cm}^2 E_{cm}^2} |f_{\psi\psi}|^2 \quad (4)$$

follows

$$\sigma_{el} = \frac{\sigma_{tot}^2(J/\psi N)|t_{eff}|(1+\eta^2)}{16\pi} . \quad (5)$$

$|t_{eff}|$ comes from the integration of eq. (4) over t . η is the ratio of the real part to the imaginary part of the amplitude of $J/\psi N$ scattering. The t -dependence of the differential cross section is given by the square of the two-gluon-form factor [12], which is

$$F_{2g}^2(t) = \frac{1}{\left(1 - \frac{t}{m_{2g}^2}\right)^4} . \quad (6)$$

with $m_{2g}^2 \approx 1.1 \text{ GeV}^2$.

And the two-gluon-form factor of the J/ψ , calculated as the nonrelativistic limit of the diagrams shown in fig. 1 is

$$F_\psi(t) = \frac{\int \Psi(z, k_t) \Delta(k_t) \Psi(z, k_t - zq_t) d^2 k_t \frac{dz}{z(1-z)}}{\int \Psi(z, k_t) \Delta(k_t) \Psi(z, k_t) d^2 k_t \frac{dz}{z(1-z)}} . \quad (7)$$

Here, Ψ is the wave function of the J/ψ , z is the fraction of the longitudinal momentum of the charmonium state carried by the c -quark, while k_t is the relative transverse momentum of the c -quark and the \bar{c} -quark. $\Delta(k_t)$ is two dimensional Laplace operator. q_t is the sum of the momenta of the two gluons. This form factor unambiguously follows from the analysis of Feynman

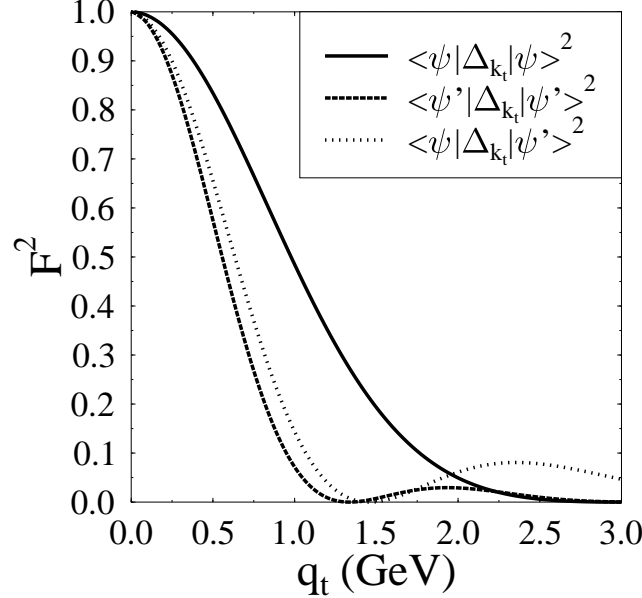


Figure 2: The form factors squared of the diagonal ($J/\psi \rightarrow J/\psi$ and $\psi' \rightarrow \psi'$) and the nondiagonal transitions ($J/\psi \rightarrow \psi'$ and $\psi' \rightarrow J/\psi$).

diagrams for hard exclusive processes. By definition it is equal to one at zero momentum transfer $F_\psi(t=0) = 1$. To evaluate this form factor we use here the nonrelativistic wave functions of ref. [13].

In the gluon exchange between the charmonium and the target only one gluon polarization dominates. In QCD evolution only this contribution contains the large logarithm $\ln(m_c^2)$. Using the QCD Ward identity one can express the obtained formulae in terms of the exchange by transversely polarized gluons like in the derivation of the Weizsäcker-Williams approximation. In the nonrelativistic approximation the binding is dominated by a Coulomb potential. The Yang-Mills vertex between the Coulomb potential and transversely polarized gluons is zero. Therefore, only the interaction between the two gluons and the two heavy quarks of fig. 1 have to be taken into account in this calculation.

The nonrelativistic approximation is justified at small momentum transfer because of the large mass of the c -quark. Small momentum transfers are the most important domain because the two-gluon form factor decreases rather quickly with the momentum transfer. The result for the elastic J/ψ form factor is shown in fig. 2. Additionally, fig. 2 depicts the elastic ψ' form factor as well as the nondiagonal transition from the J/ψ into the ψ' . In fig. 3 the dependence of the form factor on the charmonium model is shown. The elastic form factors of the J/ψ and the ψ' calculated in two different charmonium models are depicted. The charmonium models are from the refs. [13, 14]. One can see that the dependence on the charmonium model is small in comparison to other uncertainties. The elastic cross section is then proportional to

$$|t_{eff}| = \int dt F_{2g}^2(t) F_\psi^2(t) \quad . \quad (8)$$

Integrating the two-gluon-form factor of ($J/\psi \rightarrow J/\psi$) over t yields

$$\int dt F_{2g}^2(t) = \frac{1}{3} m_{2g}^2 \left(1 - \left(\frac{s + m_{2g}^2}{m_{2g}^2} \right)^{-3} \right) \approx 0.4 \text{ GeV}^2 \quad . \quad (9)$$

The approximation at the end of this equation is for sufficiently high energies, where it is possible to neglect the last term. Taking into account the elastic form factor of the J/ψ reduces this value to $|t_{eff}| = 0.3 \text{ GeV}^2$.

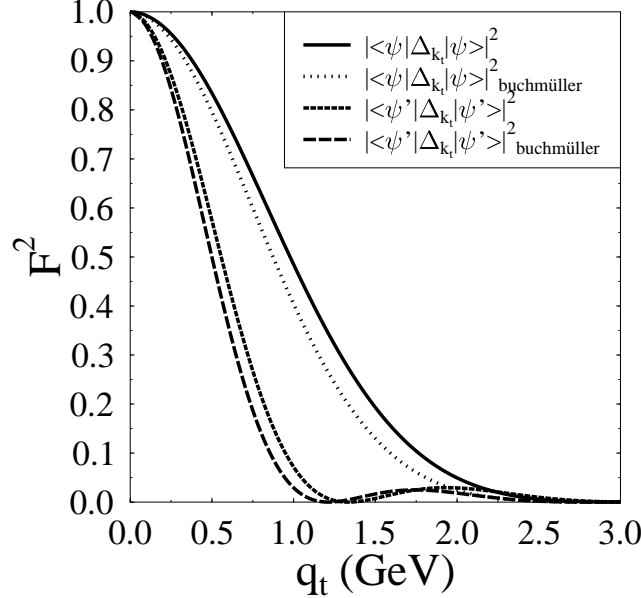


Figure 3: The form factors squared of the diagonal ($J/\psi \rightarrow J/\psi$ and $\psi' \rightarrow \psi'$) for two different nonrelativistic charmonium models.

Eq. (9) differs from the power law that arises in the limit of large t , i.e. in large angle scattering where $-t/s \sim 1/2$. In this regime, the selection of dominant diagrams follows from the requirement to obtain the lowest power of t . In the literature this is known as power counting rules. However, in the processes considered in this paper, this integral is dominated by $(-t) \cdot r_N^2 \sim 1$, where r_N is the radius of a nucleon. This kinematical region does not overlap with high-momentum transfers.

Two important phenomena are neglected in the VDM model. One is the color transparency phenomenon due to production of $c\bar{c}$ in configurations substantially smaller than the mean J/ψ size. As a result the effective cross section $\sigma_{tot}(J/\psi N)$ as extracted from the J/ψ photoproduction off a nucleon is much smaller than the genuine cross section of the J/ψ -N interaction. Another neglected effect is the hard contribution to σ_{tot} which rapidly increases with energy [9]. Therefore, we use the correspondence between the GVDM and the QCD dipole model which leads to the parametrization of cross section see ref. [2]

$$\sigma_{tot}(J/\psi N) = 3.2 \text{ mb} \left(\frac{s}{s_0} \right)^{0.08} + 0.3 \text{ mb} \left(\frac{s}{s_0} \right)^{0.2} \quad (10)$$

with $s_0 = 39.9 \text{ GeV}^2$.

It is worth noting here that such a parametrization is reasonable only for the energies where inelastic nondiffractive channels (the lowest nondiffractive channel is $\Lambda_c + \bar{D}$) are open, that is for $\sqrt{s} > 4.15 \text{ GeV}$, in the rest system of the nucleon this is $\omega > 3.61 \text{ GeV}$. The amplitudes within the GVDM are related by

$$\begin{aligned} f_{\gamma\psi} &= \frac{e}{f_\psi} f_{\psi\psi} + \frac{e}{f_{\psi'}} f_{\psi'\psi} \\ f_{\gamma\psi'} &= \frac{e}{f_\psi} f_{\psi\psi'} + \frac{e}{f_{\psi'}} f_{\psi'\psi'} \end{aligned} \quad (11)$$

The amplitudes, $f_{\psi\psi'}$ and $f_{\psi'\psi}$, that appear here additionally in comparison to the VDM in eq. (1) are the amplitudes for the nondiagonal transitions $J/\psi \rightarrow \psi'$ and $\psi' \rightarrow J/\psi$ respectively. The amplitudes following from eq. (10) and eq. (11) are given in appendix A.

The results of eq. (5) and eq. (10) (the total and the elastic cross section for $J/\psi N$ collisions) are shown in fig. 4. Fig. 5 shows the same for $\psi' N$ collisions. The ratio of the elastic to the total cross section is depicted in fig. 6.

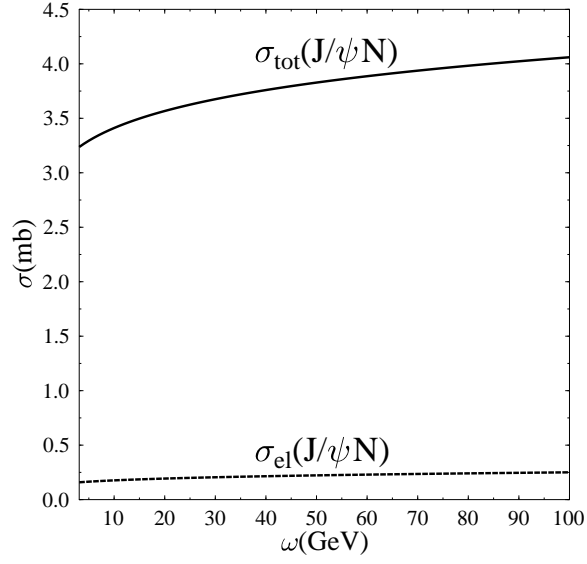


Figure 4: The elastic and the total J/ψ -nucleon cross section in dependence of the energy of the J/ψ in the rest frame of the nucleon.

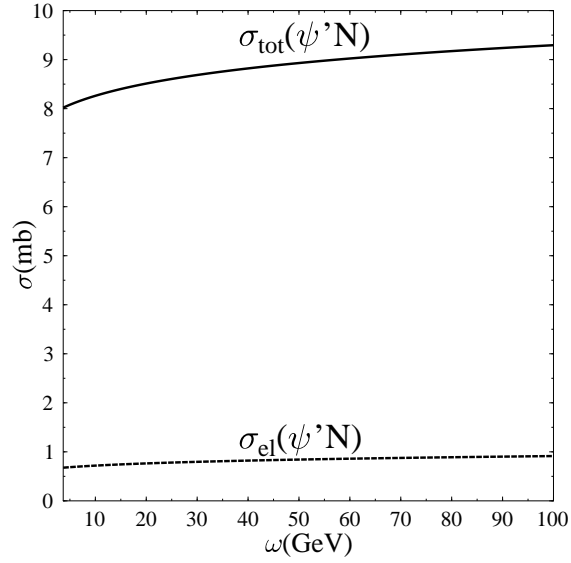


Figure 5: The elastic and the total ψ' -nucleon cross section in dependence of the energy of the ψ' in the rest frame of the nucleon.

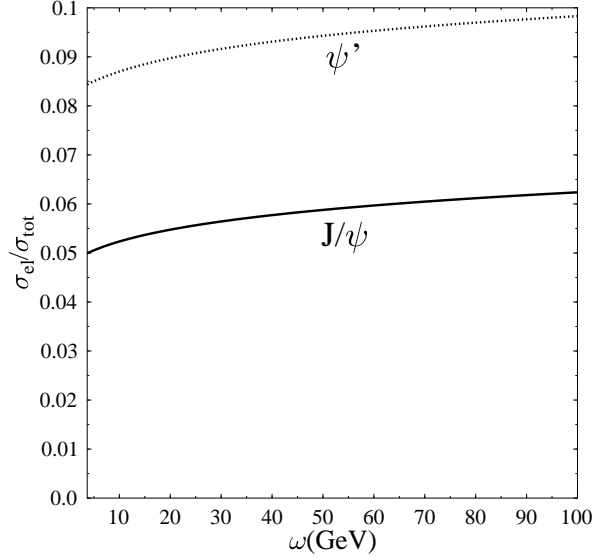


Figure 6: The ratio of the elastic charmonium-nucleon cross section to the total charmonium-nucleon cross section in dependence of the energy of the charmonium in the rest frame of the nucleon.

The elastic cross section calculated with and without the real part of the amplitude is shown in fig. 7. The real part contributes approximately 2% to the elastic cross section in the discussed energy range.

Fig. 8 shows the energy dependence of the elastic J/ψ -nucleon cross section, the elastic ψ' -nucleon cross section and the nondiagonal cross section ($\psi' + N \rightarrow J/\psi + N$). One can see that the nondiagonal cross section ($\psi' + N \rightarrow J/\psi + N$) is comparable with the elastic J/ψ -nucleon cross section.

3 $\bar{p}A$ collisions at the ψ' and the J/ψ threshold

A program of studies of charmonium production in a $\bar{p}A$ collisions at a \bar{p} accumulator is planned [15]. Hence we discuss in this section the production of charmonium states in the antiproton-nucleus collisions at the ψ' threshold. The direct production of J/ψ 's is suppressed here. However, a ψ' is produced and becomes an J/ψ in a further collision with a nucleon in the nuclear target. Since the produced hidden charm state has a large momentum relative to the nucleus target the semiclassical Glauber-approximation can be used. In our calculation we will neglect color transparency effects in the initial state for the production of J/ψ and ψ' mesons [18], since the coherence length for the fluctuation of the incoming antiproton into a small configuration is very small at the relevant energies practically completely washing out the CT effect [19].

The production of a J/ψ at the threshold in a $\bar{p}A$ collision and the subsequent production of a ψ' in a rescattering of the J/ψ , is not well suited for the measurements of the nondiagonal cross sections. This is because in a $\bar{p}A$ collision at $\sqrt{s} = m_\psi = 3.1$ GeV the J/ψ is produced at rest in the center of mass system. This means the energy in the center of mass of the J/ψ and the nucleon is 4.5 GeV. The threshold for the production of a ψ' in such a collision is $m_{\psi'} + m_N = 4.626$ GeV. This boundary is extended when nucleon Fermi motion within the nuclear target is taken into account (see ref. [19] for the discussion of the role of Fermi motion effects in the production of charmonium states).

However, this process is strongly suppressed by the phase space. At the same time, the process $J/\psi + p \rightarrow \Lambda_c + \bar{D}$ is likely to dominate the inelastic cross section. Hence the measurement of

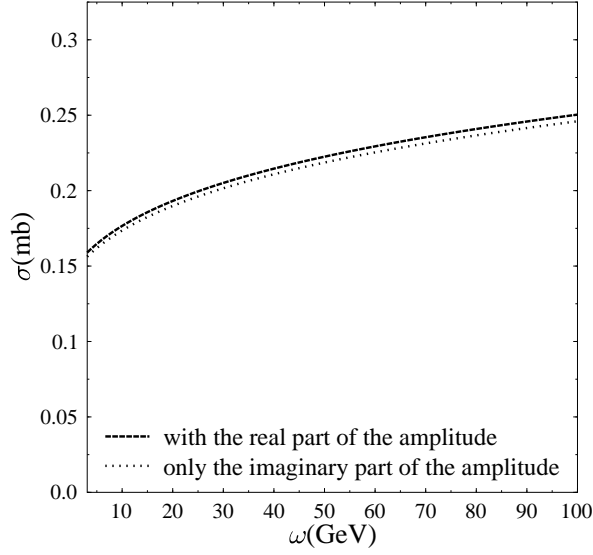


Figure 7: The elastic J/ψ -nucleon cross section in dependence of the energy of the J/ψ in the rest frame of the nucleon is shown with and without the real part of the amplitude.

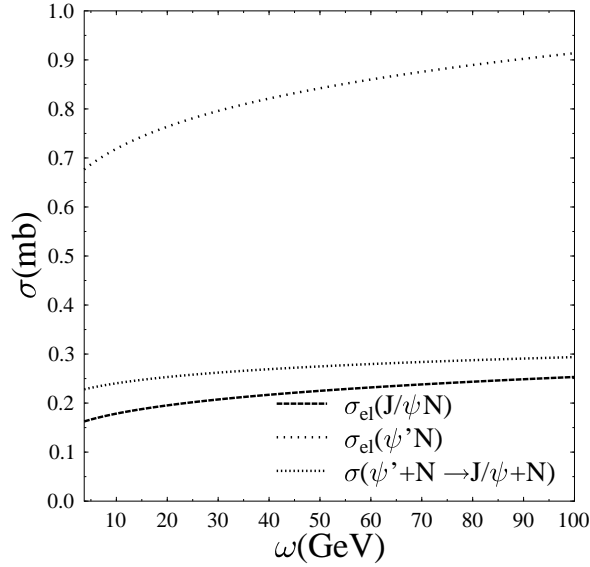


Figure 8: The elastic J/ψ -nucleon cross section, the elastic ψ' -nucleon cross section and the nondiagonal cross section ($\psi' + N \rightarrow J/\psi + N$) in dependence of the energy of the charmonium in the rest frame of the nucleon.

the process $\bar{p} + A \rightarrow \Lambda_c + \bar{D} + X$ in the vicinity of $s_{\bar{p}p} = m_{J/\psi}^2$ will allow a direct measurement of $\sigma_{inel}(J/\psi N)$.

In the semiclassical Glauber-approximation the cross section to produce a ψ' in an antiproton-nucleus collision is

$$\begin{aligned} \sigma(\bar{p} + A \rightarrow \psi') &= 2\pi \int db \cdot b dz_1 \frac{n_p}{A} \rho(b, z_1) \sigma(\bar{p} + p \rightarrow \psi') \exp\left(-\int_{-\infty}^{z_1} dz \sigma_{\bar{p}N_{inel}} \rho(b, z)\right) \\ &\quad \times \exp\left(-\int_{z_1}^{\infty} dz \sigma_{\psi'N_{inel}} \rho(b, z)\right). \end{aligned} \quad (12)$$

In this formula, b is the impact parameter of the antiproton-nucleus collision, n_p is the number of protons in the nuclear target, z_1 is the coordinate of the production point of the ψ' in beam direction, and ρ is the nuclear density. $\sigma(\bar{p} + p \rightarrow \psi')$ is the cross section to produce a ψ' in an antiproton-proton collision. $\sigma_{\bar{p}N_{inel}}$ is the inelastic antiproton-nucleus cross section. $\sigma_{\psi'N_{inel}}$ is the inelastic ψ' -nucleon cross section.

All the factors in eq. (12) have a rather direct interpretation. $\exp\left(-\int_{-\infty}^{z_1} dz \sigma_{\bar{p}N_{inel}} \rho(b, z)\right)$ gives the probability to find an antiproton at the coordinates (b, z_1) , which accounts for its absorption, and $\frac{n_p}{A} \rho(b, z_1) \sigma(\bar{p} + p \rightarrow \psi')$ is the probability to create a ψ' at these coordinates. The factor $\frac{n_p}{A}$ accounts for the fact that close to the threshold the antiproton can produce a ψ' only in an annihilation with a proton but not with a neutron. The term $\exp\left(-\int_{z_1}^{\infty} dz \sigma_{\psi'N_{inel}} \rho(b, z)\right)$ gives the probability that the produced ψ' has no inelastic collision in the nucleus, i.e. that it survives on the way out of the nucleus.

Then, in the semiclassical Glauber-approximation the cross section to subsequently produce a J/ψ in an antiproton-nucleus collision is

$$\begin{aligned} \sigma(\bar{p} + A \rightarrow J/\psi + X) &= \\ 2\pi \int db \cdot b dz_1 dz_2 \theta(z_2 - z_1) \frac{n_p}{A} \rho(b, z_1) \sigma(\bar{p} + p \rightarrow \psi') \exp\left(-\int_{-\infty}^{z_1} dz \sigma_{\bar{p}N_{inel}} \rho(b, z)\right) \\ &\quad \times \exp\left(-\int_{z_1}^{z_2} dz \sigma_{\psi'N_{inel}} \rho(b, z)\right) \sigma(\psi' + N \rightarrow \psi + N) \rho(b, z_2) \exp\left(-\int_{z_2}^{\infty} dz \sigma_{\psi N_{inel}} \rho(b, z)\right). \end{aligned} \quad (13)$$

The factor $\exp\left(-\int_{z_1}^{z_2} dz \sigma_{\psi'N_{inel}} \rho(b, z)\right)$ is the probability to find, at the coordinate (b, z_2) , a ψ' that was produced at (b, z_1) . $\sigma(\psi' + N \rightarrow \psi + N) \rho(b, z_2)$ is the probability that a ψ' collides at the coordinate (b, z_2) with a nucleon and that a J/ψ is produced. Finally, $\exp\left(-\int_{z_2}^{\infty} dz \sigma_{\psi N_{inel}} \rho(b, z)\right)$ is the probability that the outgoing J/ψ has no inelastic interactions. $\theta(z_2 - z_1) = 0$ for $z_2 < z_1$, and $\theta(z_2 - z_1) = 1$ for $z_2 > z_1$, this takes into account that a ψ' has to be produced before it can collide again.

In fig. 9 the ratio of the production cross section of the J/ψ of eq. (13) to that of the ψ' eq. (12) versus the size of the nuclear target A is plotted. Shown are the nuclear targets O, S, Cu, W, and Pb. The density distributions are from ref. [16]. In contrast to eqs. (12) and (13), the ratio doesn't depend on the cross section $\sigma(\bar{p} + p \rightarrow J/\psi + X)$, which is not well known at the threshold.

In fig. 9 we used five sets of parameters. "normal" means that the inelastic antiproton-nucleon cross section is $\sigma_{\bar{p}N_{inel}} = 50$ mb, the inelastic cross section of the ψ' is $\sigma_{\psi'N_{inel}} = 7.5$ mb, the

inelastic cross section of the J/ψ is $\sigma_{\psi N_{inel}} = 0$ mb, and the cross section for the nondiagonal transition $\psi' + N \rightarrow J/\psi + N$ is $\sigma_{\psi' + N \rightarrow \psi + N} = 0.2$ mb. The other sets differ by only one of these parameters each:

- In "ψ-absorption" $\sigma_{\psi N_{inel}} = 3.1$ mb.
- In "large ψ' absorption" $\sigma_{\psi N_{inel}} = 15$ mb.
- In "small nondiagonal" $\sigma_{\psi' N \rightarrow \psi N} = 0.1$ mb.
- In "large nondiagonal" $\sigma_{\psi' N \rightarrow \psi N} = 0.4$ mb.

One can see that the result depends much more strongly on the nondiagonal cross section than on the absorption cross sections of the J/ψ and the ψ' . Therefore, this process is well suited to measure the nondiagonal cross section. However, it will be necessary to differ between J/ψ 's produced in rescatterings of ψ' and those which come from the decays of the ψ' ¹. However, J/ψ 's produced in ψ' decays have longitudinal momenta which differ strongly from those produced in the two step processes and hence could be easily separated.

In antiproton-nucleus collisions at the ψ' threshold, predominantly ψ' mesons are produced, i.e. the direct ($p\bar{p} \rightarrow J/\psi$) production of J/ψ mesons is strongly suppressed since this would require huge Fermi momenta of the nucleons. Therefore, there are two sources of J/ψ production in this case. One source the nondiagonal transitions where a produced ψ' interacts in the final state via $\psi' N \rightarrow J/\psi N$. The other source is the decay of $\psi' \rightarrow J/\psi + X$, where X could be two pions or other hadrons. Because the ψ 's decay outside of the nucleus, the second reaction can be eliminated experimentally. The momenta of the J/ψ s in these two mechanisms are quite different. In particular, in the second mechanism $y_{cms} \sim 0$ and the distribution is symmetric around $y = 0$, while in the nondiagonal mechanism there is a shift to rapidities closer to y_A . For a rescattering without transfer of transverse momentum, this is a shift of 0.2 units of rapidity, with transverse momentum transfer the shift would be larger. In the center of mass system this is a shift of $\Delta p_{cms} = 0.6$ GeV. In the laboratory system a J/ψ produced at $y_{cms} = 0$ has momentum of 6.1 GeV the J/ψ 's produced in nondiagonal transitions have an average momentum of at most 4.2 GeV.

At the J/ψ threshold the only possibility for an inelastic interaction of the produced J/ψ is the channel $J/\psi + N \rightarrow \Lambda_c + D$. At the ψ' threshold next to the channel $\psi' + N \rightarrow \Lambda_c + D$, $\psi' + N \rightarrow N + D + \bar{D}$ is also kinematically allowed. However, in the strange sector the channel $\phi + N \rightarrow N + K + \bar{K}$ is strongly suppressed versus the channel $\phi + N \rightarrow \Lambda + K$, therefore it is very likely that the $\Lambda_c + D$ channel dominates at both energies, the J/ψ threshold and the ψ' threshold.

The cross section for the production of ψ' that doesn't undergo an inelastic rescattering is $\sigma(\bar{p} + A \rightarrow \psi' + \text{nuclear fragments})$ is given by eq. (12). The cross section for the production of ψ' , whether they have subsequent inelastic scatterings or not is given by

$$\sigma(\bar{p} + A \rightarrow \psi')_{w/oinel} = 2\pi \int db \cdot b dz_1 \frac{n_p}{A} \rho(b, z_1) \sigma(\bar{p} + p \rightarrow \psi') \exp\left(-\int_{-\infty}^{z_1} dz \sigma_{\bar{p}inel} \rho(b, z)\right) . \quad (14)$$

Assuming that the Λ_c channel is the only possible final state in inelastic collisions (i.e. the $D\bar{D}$ channel as well as the nondiagonal transition is neglected as a correction here), the fraction of the initially produced ψ' that ends up in the Λ_c channel is

$$\frac{N_{\Lambda_c}}{N_{\psi'initial}} = 1 - \frac{\sigma(\bar{p} + A \rightarrow \psi' + \text{nuclear fragments})}{\sigma(\bar{p} + A \rightarrow \psi' + \text{nuclear fragments})_{w/oinel}} . \quad (15)$$

Here we neglected the final state interactions of Λ_c as they may only effect the momentum distribution of Λ_c since the Λ_c energy is below the threshold for the process $p + \Lambda_c \rightarrow N + N + D$. For

¹The experiments also have to be able to detect radiative decays, because the ψ' decays with a probability of 8.4% and 6.4% respectively into a photon and a χ_{c1} and a χ_{c2} respectively, which decay with a probability of 31.6% and 20.2% respectively into a photon and a J/ψ [17]. In total this gives $8.4\% \cdot 31.6\% + 6.4\% \cdot 20.2\% = 3.9\%$, which is of the same order of magnitude as the nondiagonal transitions.

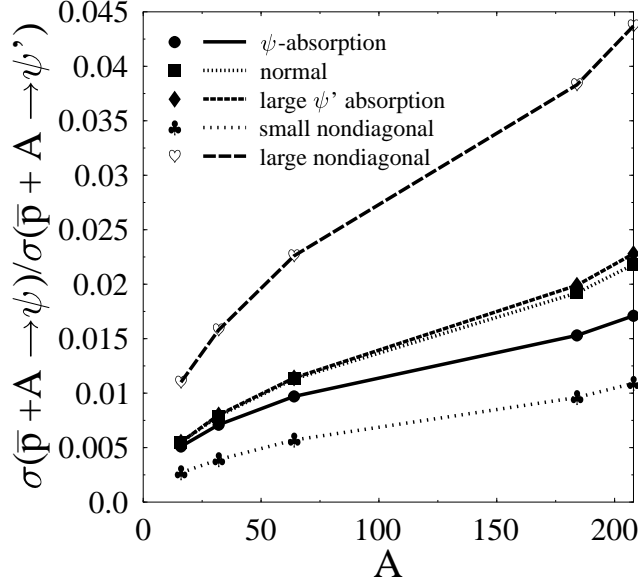


Figure 9: The ratio $\sigma(\bar{p} + A \rightarrow \psi + \text{nuclear fragments}) / \sigma(\bar{p} + A \rightarrow \psi' + \text{nuclear fragments})$ is shown for 5 different sets of parameters (see text for further details). Shown are the nuclear targets O, S, Cu, W, and Pb. The lines are just to guide the eye.

this reaction the Λ_c would need an energy of 4.2 GeV in the rest frame of the proton, while it has in average less than 3 GeV. The change of the momentum distribution of Λ_c would provide unique information about the $\Lambda_c N$ interaction and could be a promising method for forming charmed hypernuclei. Obviously eq. 15 is valid also for \bar{D} production. The fraction for the ψ' and the J/ψ threshold is depicted in fig. 10. Note that in eq. (15) and fig. 10 the denominator is the number of produced particles, while in fig. 9 the denominator is the number of ψ' that don't undergo subsequent inelastic scatterings only.

4 Conclusion

We found that accounting for color transparency phenomena within the GVDM leads to a ratio of the elastic J/ψ nucleon cross section to the total J/ψ nucleon cross section of approximately $5\% \div 6.5\%$. This value is significantly larger than that which follows from the analysis based on VDM cf. [10], where 2% was found. Note that in ref. [10] $|t_{eff}| = 1/6 \text{ GeV}^2$ has been taken from soft QCD process of the photoproduction of ρ mesons, while the value following from the two gluon form factor extracted from the photoproduction of J/ψ mesons within the framework of the QCD factorization theorem and the form factor of the J/ψ is closer to $|t_{eff}| = 0.4 \text{ GeV}^2$. Also, the total J/ψ -nucleon cross section fitted with the VDM to the data is approximately a factor two smaller than the value obtained within the GVDM.

This result is in agreement with naive expectations. The ratio of the elastic cross section to the total cross section known for the pion or the proton projectiles is approximately 25%. The total J/ψ -nucleon cross section is significantly smaller than the total π -nucleon cross section, because the J/ψ has a much smaller size than the π (the radius of the J/ψ is a factor 4 smaller than the one of the π). Therefore the interaction of the J/ψ with a nucleon is much weaker than the π -nucleon interaction due to a stronger screening of color charge of the constituents. That is also why the J/ψ N interaction is further from the black disk limit than the π . Measurements in $\bar{p}A$ collisions will allow one to get new information about the strength of the inelastic $J/\psi N$ and $\psi' N$ interactions leading to the production of Λ_c and \bar{D} and for the first time about nondiagonal

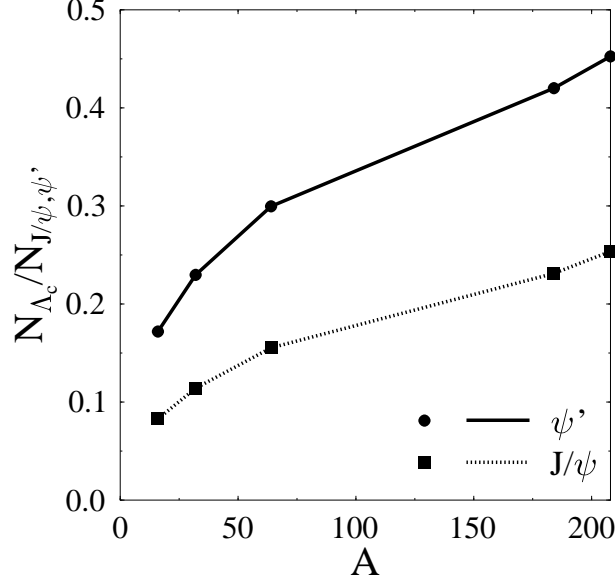


Figure 10: The ratio of the number of Λ_c divided by the number of produced J/ψ and ψ' respectively states at the threshold of J/ψ and ψ' production respectively. Shown are the nuclear targets O, S, Cu, W, and Pb. The lines are just to guide the eye.

transitions, $\psi' N \rightarrow J/\psi N$.

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A Appendix: Amplitudes from the GVDM

The imaginary part of the amplitude of the forward scattering of a J/ψ on a nucleon is given by the cross section of eq. (10) and the optical theorem

$$I_{\psi\psi} = 2\sqrt{s}p_{cm} \left(8 \left(\frac{s}{s_0} \right)^{0.08} + 0.75 \left(\frac{s}{s_0} \right)^{0.2} \right) \text{ GeV}^{-2} \quad . \quad (16)$$

The real part of the amplitude can be evaluated with the help of the Gribov Migdal relation

$$R_{\psi\psi} = \frac{\sqrt{s}p_{cm}\pi}{2} \frac{\partial}{\partial \ln s} \frac{I_{\psi\psi}}{\sqrt{s}p_{cm}} \quad . \quad (17)$$

This yields

$$R_{\psi\psi} = \pi\sqrt{s}p_{cm} \left(0.64 \left(\frac{s}{s_0} \right)^{0.08} + 0.15 \left(\frac{s}{s_0} \right)^{0.2} \right) \text{ GeV}^{-2} \quad . \quad (18)$$

The nondiagonal amplitudes and the amplitudes for the ψ' is given in the GVDM by

$$f_{\gamma\psi} = \frac{e}{f_{\psi}} f_{\psi\psi} + \frac{e}{f_{\psi'}} f_{\psi'\psi}$$

$$f_{\gamma\psi'} = \frac{e}{f_\psi} f_{\psi\psi'} + \frac{e}{f_{\psi'}} f_{\psi'\psi'} \quad , \quad (19)$$

e is the charge of an electron and f_ψ is the $J/\psi - \gamma$ coupling. $f_{\gamma\psi}$ is the J/ψ photoproduction amplitude and $f_{\psi\psi}$ the J/ψ -nucleon elastic scattering amplitude. The amplitudes $f_{\psi\psi'}$ and $f_{\psi'\psi}$ are the amplitudes for the nondiagonal transitions $J/\psi \rightarrow \psi'$ and $\psi' \rightarrow J/\psi$ respectively.

We assume that the real part of the amplitudes $f_{\gamma\psi}$ and $f_{\gamma\psi'}$ can be neglected. This is realistic, because $f_{\gamma\psi} \ll f_{\psi\psi}$. Note that $f_{\psi\psi'} = f_{\psi'\psi}$, because of the CPT invariance of the amplitude. Then real parts of the two other amplitudes are

$$\begin{aligned} R_{\psi'\psi} &= -\frac{f_\psi}{f_{\psi'}} R_{\psi\psi} = -1.7 \cdot R_{\psi\psi} \\ R_{\psi'\psi'} &= -\frac{f_\psi}{f_{\psi'}} R_{\psi'\psi} = -1.7 \cdot R_{\psi'\psi} = 2.9 \cdot R_{\psi\psi} \quad . \end{aligned} \quad (20)$$

For their imaginary parts follows

$$\begin{aligned} I_{\psi'\psi} &= \frac{f_{\psi'}}{e} I_{\gamma\psi} - \frac{f_\psi}{f_{\psi'}} I_{\psi\psi} = 2\sqrt{s} p_{cm} \cdot 136.5 \cdot \left(\frac{s^{0.2}}{s_0^{1.2}} \right) - 1.7 \cdot I_{\psi\psi} \\ I_{\psi'\psi'} &= \frac{f_{\psi'}}{e} I_{\gamma\psi'} - \frac{f_\psi}{f_{\psi'}} I_{\psi'\psi} = \frac{f_{\psi'}}{e} I_{\gamma\psi'} - 1.7 \cdot I_{\psi'\psi} = \frac{f_{\psi'}}{e} I_{\gamma\psi'} + -1.7 \cdot \frac{f_{\psi'}}{e} I_{\gamma\psi} + 2.9 \cdot I_{\psi\psi} \\ &= 2\sqrt{s} p_{cm} \cdot 175.5 \cdot \left(\frac{s^{0.2}}{s_0^{1.2}} \right) + 2.9 \cdot I_{\psi\psi} \quad . \end{aligned} \quad (21)$$

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